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EFFECT OF CYCLIC ELECTRIC FIELDS ON CRACK GROWTH IN A MODERATELY SOFT PIEZOELECTRIC CERAMIC

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ABSTRACT

Pre-existing cracks introduced by a Vickers diamond hardness indenter in BM500 (Navy Type 1I) PZT exhibit visible growth and thickening when subjected to low frequency electric fields with amplitudes above a threshold on the order of 1.66 E_c. Thickening, but no growth, of cracks is also observed after cycles of a field of 1.64 E_c. The threshold field is related to the ferroelectric, piezoelectric and elastic properties of the ceramic. At fields above the threshold, cracks grow to a limiting size after a relative low number of cycles, and then increase in width, as opposed to length, when further electric cycles are applied. The maximum size to which field-induced cracks grow is of the order of the separation of the electrodes. Changes observed in the resonance peaks of impedance spectra may be used as a basis for non-destructive identification of defects in piezoelectrics.

INTRODUCTION

Cracks generated by a Vickers hardness diamond indenter have been observed to grow in a direction normal to a low frequency applied electric field in relatively soft piezoelectrics, such as 58/42 lead zirconate titanate (PZT) [1], 8/65/35 lead lanthanum zirconate titanate (PLZT) [2], BM532 (Navy Type VI) PZT [3] and BM660 [4], which is a 70/30 lead magnesium niobate-lead titanate (PMN-PT [5]. When these piezoelectrics were subjected to cyclic electric fields up to 3 times the coercive field, E_c, some investigators observed that crack growth was proportional to crack length [1], while others have reported that pre-existing cracks grow to a limiting size, which is determined by the geometry of the specimen [2] and/or the magnitude of the applied field [3,4].

To investigate further the incidence of field induced crack growth in soft piezoelectric materials, additional crack growth experiments have been conducted on BM500 (Navy Type II) PZT, which has moderately soft piezoelectric properties. As indicated by the data in Table 1, the BM500 dielectric constant K_{33}, piezoelectric coupling factor k_{33}, charge constant d_{33} and mechanical compliance S_{33} are of the same order as those of the previously examined BM532 (Navy Type VI) PZT, but are of lower magnitude. In addition to examining the extent of crack growth as a function of applied electric field intensity and number of cycles, the effect of the observed crack growth on the impedance and resonance frequencies of the specimens was also investigated to follow up a previous observation that that crack extension in piezoelectrics may be detected nondestructively from impedance measurements [7].

Table 1. Dielectric and Piezoelectric Properties of Industrial PZTs

Property	**BM532**	**BM500**	**Units**
T_c	210	360	°C
K_{33}	3250	1750	--
Tan δ	2.5	2.5	%
E_c	0.88*	1.2**	MV/m
k_{33}	0.75	0.72	--
d_{33}	630	365	10^{-12} C/N
g_{33}	20	22	10^{-3} Vm/N
Q_M	70	70	--
N_3	1750	1800	Hz.m
S_{33}	20.0	19.0	$10^{-12}m^2/N$

Data published by SensorTechnology [6].
* Ref. [3]. ** Private communication from SensorTechnology.

EXPERIMENTAL METHODS

Powder of BM500 was synthesized at Sensor Technology Ltd., Collingwood, ON, by mixing, grinding and calcining component oxide powders. Sintered ceramics prepared from these powders were cut and ground to dimensions of 12.7 mm x 3 mm x 1.27 mm. The 12.7 mm x 3 mm faces of the specimens were screen printed with silver paste to form electrodes for applying electric fields for poling the specimens and for the crack growth experiments. The narrow 1.27 mm x 12.7 mm faces were polished with silicon carbide and then lapped with 6 µm diamond paste, to obtain a smooth flat surface, which was indented with a Vickers diamond pyramid, by applying a load of 20 N for 10 s. During this operation, the samples were oriented in the hardness tester so that one set of the corners of the diamond indent was aligned parallel, and one set normal, to the silvered electrode faces. Two specimens were not indented, to provide reference standards for comparative impedance measurements, in which the length thickness extensional (LTE) mode resonance was measured to an accuracy of ± 1 kHz, using an Agilent 4294A precision impedance analyzer.

For studying the effect of cyclic electric fields, the specimens were mounted in a specially designed jig, which was placed on the translational stage of an optical microscope, as described previously [4]. Cyclic fields with a frequency of 5 Hz and amplitudes up to 3.5 kV, were applied for successive cycles using a Trek 609E-6 high voltage amplifier, controlled by a computer via the SS05 polarization meter. With the narrow specimen width of 1.27mm the maximum selected output of 3.5 kV from the Trek instrument generated a maximum field of 2.76 MV/m across the electrode faces of the specimens. The samples were thus not vulnerable to dielectric breakdown, which typically occurs in the range of 4-8 MV/m in PZT [8]. To prevent possible arcing at high applied fields, the sample and contacts were immersed in insulating oil. After each application of a selected number of voltage cycles, changes in the length of pre-existing cracks oriented normal to the field were determined *in situ* to an accuracy of ± 50 μm by traversing a cross hair in the objective lens from one end of the crack to another at a magnification of 40X, as described previously [4]. At the termination of the cyclic field experiments, the cracks were re-measured in a higher power microscope at magnifications of 160-400X using the knife edges in the Vickers hardness microscope.

RESULTS AND DISCUSSION

For experimental purposes, the total length of a crack was taken as the sum of the two lengths emanating from the corners of the indent, plus the width across the corners of the indent. Cracks generated by the Vickers indentation were typically between 250-300 μm. In many samples, these cracks were barely discernable in the as-indented condition, but crack widening was observed after 1000 cycles at 1.31 E_c, after 10 cycles at 1.64 E_c, after 500 cycles at 1.77 E_c and after 500 cycles at 1.97 E_c. As indicated below, this crack widening occurred at field/cycle combinations below the level to induce an increase in crack length.

The effect of cycles of applied field of various amplitudes at a common frequency of 5 Hz on crack lengths is shown in Figure 1. No change in crack length was observed after increasing numbers of cycles up to 1000 in reduced fields ≤ 1.64 E_c On increasing the field to 1.77 E_c, crack extension was observed after 500 cycles, but no further increase in crack length was observed after 1000 cycles. In a field of 1.97 E_c, the cracks were extended up to 0.94 mm after successive cycles up to 1000. Two further specimens were exposed to 2000 cycles in a field of 2.30 E_c, after which the cracks were extended to 0.93 and 1.04 mm. Although the number of data points is relatively few, it is evident that the cracks increase up to a limiting length for a given applied field and then show no further extension with increasing field cycles, in agreement with previous studies on PLZT [2] and BM532 [3]. Also, the maximum size of the extended cracks approaches the separation of the electrodes (1.27 mm), as noted in previous studies [2,3].

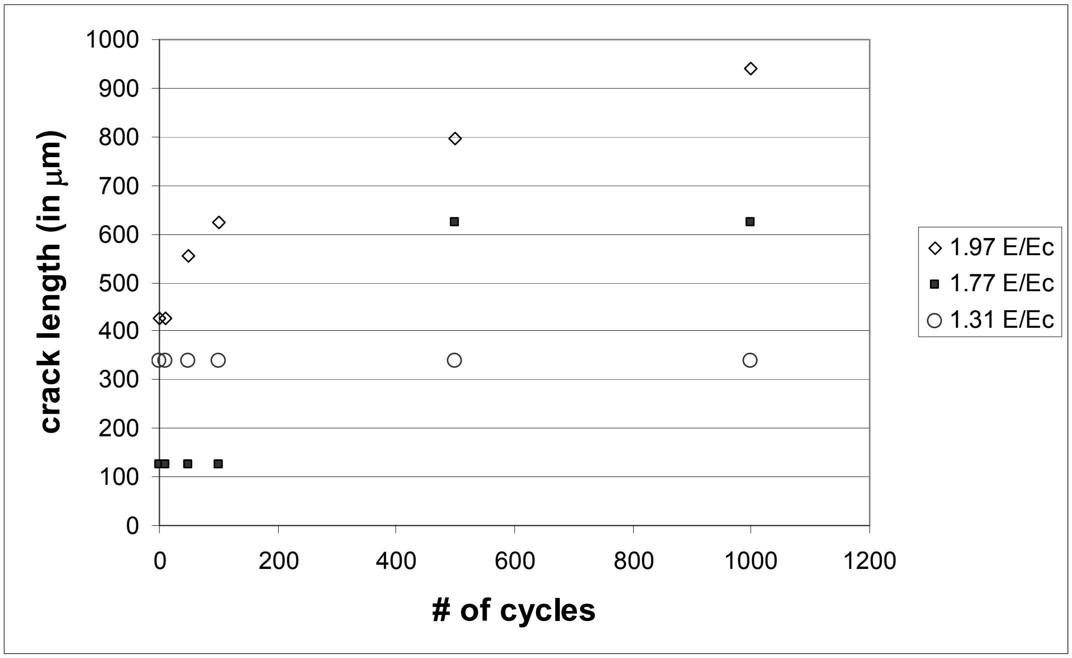

Fig. 1. Crack length vs. number of cycles, for various fields at 5Hz.

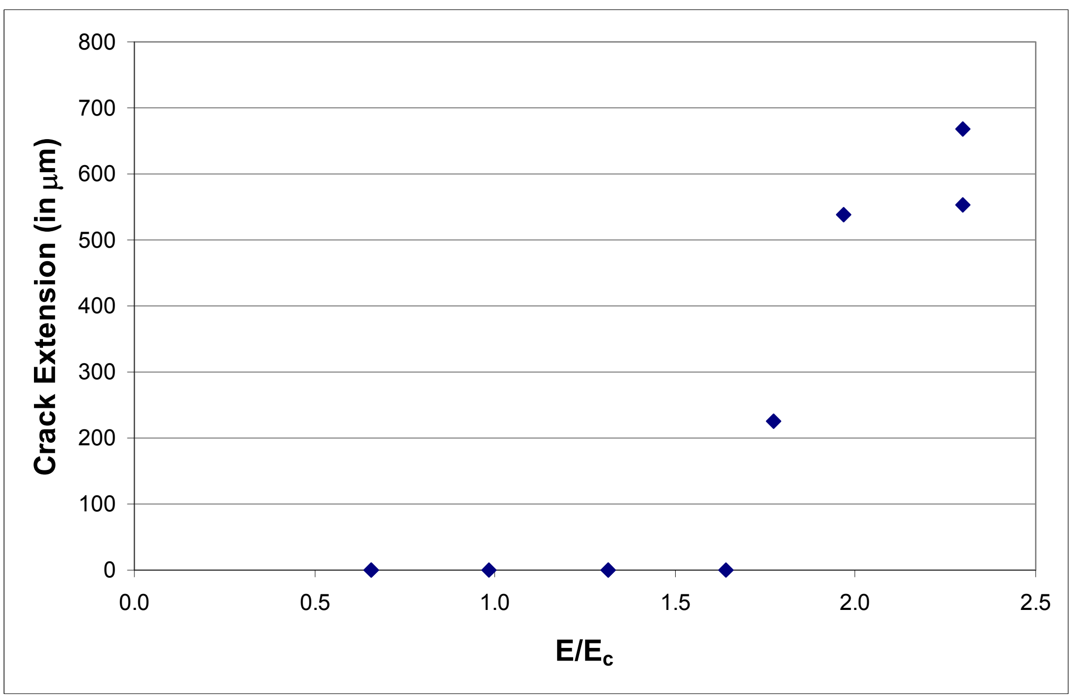

Fig. 2. Crack extension after 1000 cycles vs. reduced field at a frequency of 5 Hz.

The effect of peak to peak field intensity on crack extension after 1000 cycles at a common frequency of 5 Hz, is shown in Figure 2. No change in crack length was observed in reduced fields up to 1.64 E_c, but a significant and progressive increase in crack length occurs in increasing fields over the range from 1.77–2.30 E_c. This increasing field behaviour is analogous to the increase in field-induced crack growth rate observed previously in other soft piezoelectrics such as PLZT [2] and BM532 [3]. The results also show that a threshold field of the order of 1.66 E_c is necessary to develop sufficient electric stress to propagate a crack in BM500. Cracks have previously been observed to grow at a lower reduced field of 0.9 E_c in the soft piezoelectrics 58/42 PZT [1] and BM532 [3], and in a reduced field of 1.2 E_c in 8/65/35 PLZT [2]. These ceramics are characterized by lower coercive fields and greater piezoelectric strain constants and mechanical compliance, as indicated in Table 1. The requirement of a threshold field related to ferroelectric, piezoelectric and elastic properties may thus be the reason why crack growth is not observed when harder piezoelectrics, such as BM800 and BM200 [7], are subjected to applied fields up to the safe maximum of 3.15 MV/m.

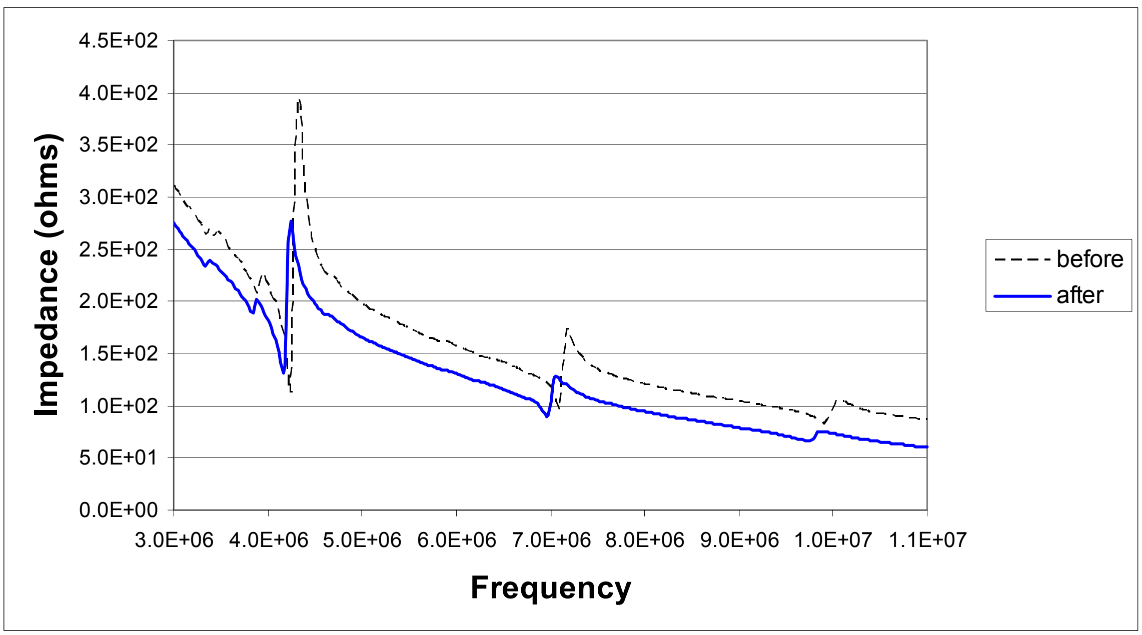

Fig. 3 LTE impedance spectra for as-indented and electrically cycled BM500 at 1000 cycles.

<u>Impedance Spectra Measurements</u>

The effect of a crack grown to 0.94 mm, by an applied field of 1.97 E_c for 1000 cycles, on the LTE mode impedance spectra of a sample of BM500 is shown in Figure 3. The resonance peaks are diminished in size, and also displaced to lower frequencies, by the extension of the crack. The magnitudes of these impedance changes and peak shifts are significantly greater than equivalent impedance effects observed previously in the hard piezoelectrics BM200 and BM800 [7] and clearly indicate that these parameters can be used as viable indicators of the presence and size of mechanical defects that create internal surfaces within a piezoelectric sensor or actuator. A more quantitative correlation between crack dimensions and impedance spectra changes in presently under investigation and will be presented in the near future.

SUMMARY AND CONCLUSIONS

The overall observations and conclusions of the present experiments are:

1. Microscopic examination showed that cracks emanating from the corners of Vickers indents in the PZT BM500 extend over a total distance of 250-300 μm.
2. Crack growth in cyclic electric fields does not occur below a threshold electric field on the order of 1.66 E_c, though crack widening is observed at 1.31 E_c.
3. The threshold field for field-induced crack propagation is related to the ferroelectric, piezoelectric and elastic properties of a ceramic.
4. In fields of 1.77 E_c. and above, cracks grow to a limiting size after a relative low number of cycles, and then increase in width, as opposed to length, when further electric cycles are applied.
5. The maximum size to which field-induced cracks grow approaches the order of the separation of the electrodes.
6. Resonance peaks in the impedance spectra of BM500 are diminished in magnitude and displaced to lower frequencies by the presence of a crack. Such changes may be used as a basis for non-destructive identification of defects in piezoelectrics.

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